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Comprehensive assessment of the long-term energy harvest capabilities for PV systems with different tilt angles: Case study in Taiwan

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ABSTRACT

This paper presents an overview of assessments of the long-term energy harvest capabilities of different photovoltaic (PV) systems. Based on semiconductor theory, an effective assessment approach is developed which can be used for evaluation of the ratios of energy harvested by different PV systems at various latitudes. The proposed approach makes evaluation of the theoretical and the benefits of their business applications easy to assess. To test the applicability of the proposed approach, single-axis sun-tracking type (SASTT), dual-axis sun-tracking type (DASTT), and fixed-type (FT) PV systems with various tilt angles, all with a rated power capacity of 3.68 kW, were installed in northern Taiwan (latitude of 24.92°) and experiments were conducted over a one year period. The prediction errors between theoretical simulations and long-term field verifications were less than 4%. The assessment results indicate that FT PV systems with a smaller tilt angle would be a better choice for installation in Taiwan. This finding overturns the current installation guidelines in Taiwan, i.e., FT PV systems should be installed with a tilt angle of 23.5°. The proposed assessment approach can provide data for objective comparisons of any type of PV system and offers a valuable reference for PV system installers before they invest time, money, and energy for installation.

1. Introduction

The development of reliable sources of renewable energy has attracted increasing attention in recent years. Compared with other systems reliant upon renewable energy whether it is wind, geothermal, or biomass energy, photovoltaic (PV) systems are becoming more popular because of their easy setup, stable capacity, and other factors [1–6]. The vast majority of PV systems in service are the fixed type (FT) because these have the lowest device and maintenance costs. In practice [7–11] though, the output power of a single-axis sun-tracking type (SASTT) or dual-axis sun-tracking type (DASTT) system is greater than that of an FT system. The construction cost and follow-up maintenance cost of both SASTT and DASTT systems are relatively high. There are currently no effective methods or reliable data for evaluating the tradeoff between the energy harvest and the costs of equipment and maintenance of PV systems, which often causes system-setting providers to hang back on investment. To evaluate the performance of a PV generation system in real time, the output influence of numerous environmental factors on the generation of different PV systems needs to be estimated in advance. Clearly, it is necessary to develop a comprehensive method for the assessment of the long-term energy harvest capabilities of various PV systems.

It is also necessary to consider the in-service conditions when evaluating the performance of grid-connected PV systems and power plants. The assessment of the optimal configuration of a PV system is closely related to the geographic location, tilt angle, and tracking mechanism [12–29]. Theoretical analysis and prediction of the energy harvested by PV systems has been made [12]. The authors discussed the following factors: radiation intensity; angular losses; temperature losses; mismatch losses; loss due to dust and dirt, shading, and cabling;

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loss due to differences from the nominal power; loss due to monitoring error of the power maximum peak; and loss in the inverter due to DC-AC conversion [12]. They proposed a performance ratio (PR) and established with four input parameters, including the average ambient temperature of the city, the latitude, and the orientation and tilt angles of the plane of the photovoltaic generator. The model proposed in [12] had a high accuracy and a complete simulation was performed. The model is specifically suitable for the installation of PV systems in low latitude countries.

Several studies have investigated the effects of various climatic conditions and different geographical locations on the performance of fixed and sun-tracking PV systems [13–15]. The DASTT system was found to be more suitable for grid-connected PV generators in areas with a tropical climate, compared to fixed type PV systems and PV systems with concentrating mirrors and tracking mechanisms [13]. Micheli et al. evaluated the performance of two same-sized grid-connected PV systems over one year based on two performance indices [14]. In one 30-day experimental study, it was found that the amount of energy produced could be significantly increase by 12–20% when sun-tracking was used [15]. Alata et al. used the fuzzy control method to describe the sun's motion across the sky and proposed designs for three types of multi-purpose sun tracking systems [16]. However, the fuzzy-based control method may be too complex, making implementation and control of the mechanical components and electrical circuits difficult due to the complexity of the mathematical operations. Clearly, a less complicated and more useful way to assess the energy harvesting performance of different types of PV systems is required.

Some of the findings of interesting from previous literature surveys are briefly summarized in Table 1. Some of the shortcomings of past studies include the usual adoption of simulation approaches to examine the energy harvest capabilities of different types of PV systems and the fact that few have conducted long-term experiments for verification. Furthermore, in most past studies, only the currently available commercial software has been used to assess the annual energy harvested by PV systems based on the solar irradiation. The most common technique for evaluation of the energy harvest performance of a PV system has been to focuses on the variation in irradiation under different solar incident angles regardless of what materials are utilized for the PV cells [17–23]. In these studies the energy production ratio (EPR) of tracking-type PV systems has been estimated in comparison to fixed ones. However, the variation of irradiation will only affect the input conditions of the PV modules; it is not necessarily representative of the output performance. In contrast, Senpinar and Cebeci presented a comparison of the performance of two PV modules, one fixed and the other fitted with a DASTT system which enabled the PV collector to follow the movement of the sun [17]. They compared the movement of the DASTT PV module to the mathematically calculated positions of the sun from sunrise to sunset. Overall, Senpinar and Cebeci found that the daily output power of the tracking module was 13–15% higher than for the FT module [17]. Although they did conduct field tests for comparison of the EPR between the DASTT and FT PV systems, the period of the field trial was too short to reflect the actual long term functioning of the two tested systems.

Further, an overview of research on basic solar radiation and PV generation with consideration of possible effects of environmental variation on the EPR in long-term trials has been carried out for the city of Monastir, Tunisia [18]. The performance of a complete PV model and the effectiveness of a multi-axis sun-tracking system for harvesting solar energy were examined in a case study for the city of Monastir, Tunisia [18]. It is worth noting that the effects of azimuth and tilt angles on the output power of a photovoltaic module were also investigated in this study. Unlike a south facing commercial PV system, the orientation of the DASTT PV panel in [18] was adjusted to take advantage of all available light by changing the azimuth angle to cover loads in early morning or late afternoon. The results showed that this approach would produce a 30% and 44% gain relative to a traditional fixed panel at the winter and summer solstice, respectively. However, the differences between the EPRs found in these studies are so great, ranging from 4% to 45%, that it lowers the referential value of the obtained results. These defects are mainly attributable to the shortness of the experimental period [17,19], obtaining the results directly from a simulation or a database [18–20,22], or the lack of a program of field experiments [20,22,23]. To overcome with the afore-mentioned difficulties, we have developed a method based on semiconductor theory capable of estimating the annual energy harvest ratios of SASTT and DASTT systems for comparison against those of a FT system under given input conditions [24]. However, in previous work, we did not take into consideration the effect of different tilt angles on the energy harvest capability of the FT system or the cost issue [24].

For long-term evaluation on the performance of a PV system under

Table 1
The literature survey and comparison related to this study.

Reference	System type	Evaluated items	Latitude of system location	Experiment interval	Comparative targets	Power increment[a]
[17]	Dual-axis	Irradiation variation	Turkey	Several days	FT at a slope of 52.46°	13–15%
[18]	Dual-axis and Single-axis	Irradiation variation	Tunisia	1 year (simulated)	FT at variable slopes	5.76%
[19]	Single-axis (3P-CPCs)	Irradiation variation	N/A	Several days	Single-axis (1P-CPCs)	26–45%
[20]	Single-axis	Irradiation variation	N/A	N/A	FT	20–30%
[21]	Dual-axis and Single-axis	Irradiation variation	N/A	1 year	FT at a slope of 10° (Mar.-Sep.) and 40° (Oct.-Feb.)	15%
[22]	Single-axis	Solar radiation and temperature databases	Whole Europe	N/A	FT	20–50%
[23]	Single-axis	Irradiation variation	Several Sites	N/A	FT Two-axis	28–4%
[24]	Dual-axis	Power variation	24.93°	1 year	FT at a slope of 25°	16.74%
[25]	Dual-axis and Single-axis	Irradiation variation (METEONNORM software)	Jordan	1 year (simulated)	FT	20.12–30.82%
[26]	Dual-axis	Irradiation variation (PVSYST software)	Turkey	1 year	FT with a tilt-at-latitude angle	30.79%
[27]	Dual-axis and Single-axis	Irradiation variation (NSR Database)	USA	1 year (simulated)	FT at a slope of 25°	12–25% 30–45%
[28]	Dual-axis and Single-axis	Irradiation variation (PVGIS software)	Spain	1 year (simulated)	FT at flat plate	38%
[29]	Dual-axis, Single-axis and Concentrator	N/A (DKASC data analysis)	Australia	1 year (simulated)	FT	Not mentioned
This study	Single-axis	Power variation	24.93°	6 months	FT at a slope of 23.5°	15.13%
This study	FT at a slope of 23.5°	Power variation	24.93°	1 year	FT at a slope of 0°	2.15%

[a] The power increment is defined as the gain of the comparative approaches, models, or systems compared with the origin control system.